

Small Spacecraft for Planetary Atmospheric, Surface, and Interior Structure Using Radio links

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Abstract—Scientific studies using spacecraft radio links have been conducted on almost every Solar System exploration mission in the past five decades and have led to numerous discoveries. Radio Science experiments have elucidated the thermal history of the Moon from high resolution gravitational field measurements, unveiled the interiors of Titan, Enceladus, Mercury, Phobos, Vesta and Ceres providing key evidence for identifying subsurface oceans on icy moons; sounded Titan, Saturn, and Pluto’s atmospheres, and refined models for the atmospheres, surfaces, and interior structure of Mars and Venus. A Juno experiment is in progress measuring the gravitational field of Jupiter to reveal its interior structures, as did a similar recent Cassini experiment with Saturn. Experiments at Mercury, the Jovian system, and other targets, are in development or planning phases. Over the next 30 years, significant advances in radio and laser link-science technologies, including nearly one order of magnitude improvement achievable in range-rate and range accuracy, could enable many new scientific breakthroughs. Future exploration concepts in many cases focus on applications of small spacecraft and can include spacecraft constellations for studies of atmospheric dynamics, interior structures, and surface properties. A set of science-enabling radio link technologies specific to small spacecraft instrumentation on future solar system missions are under study and development. Examples include field tests of radio scattering to determine soil properties, smallsat constellations for dense geographic and temporal atmospheric probing, small science-quality software-defined transponders, miniature ultra-stable oscillators, and advanced radio-metric calibrations at the Deep Space Network. This paper describes many of these technologies and their scientific applications.

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1. UTILIZATION OF RADIO LINKS

Radio Science observations involving precise monitoring of the radio links between a spacecraft and an antenna of NASA’s Deep Space Network (DSN) have produced a number of high profile results, including austere constraints on fundamental laws, unsurpassed probing of the outer planets’ atmospheres, and some of the initial evidence favoring sub-surface oceans on icy moons in the outer solar system. As described at NASA’s Planetary Sciences Vision 2050 Workshop [1], new technologies are becoming available that offer the possibility of significantly enhanced radio science and laser-link measurements, including small spacecraft, entry probes, aerial vehicles, software defined radios, advanced ground system instrumentation, smaller and higher precision space clocks, and interplanetary laser links developed for optical telecommunications.

Strategic development at NASA’s Jet Propulsion Laboratory (JPL) will advance selected technologies with a specific focus on developing telecommunications technologies to improve planetary atmospheric, surface, and interior investigations using small spacecraft that contribute to expanding the frontiers of solar system exploration.

All spacecraft have telecommunication links and utilizing those for high-value science further enhances the missions. CubeSats, as an example of the form factor of small spacecraft (smallsat), can benefit from this synergistic utilization. CubeSats have not yet been flown on deep space missions before. JPL teams, however, have developed the Mars Cube One (MarCO) mission comprising redundant CubeSats [2] as illustrated in Figure 1, which is scheduled for flight in 2018 to provide relay support to the InSight Mars lander entry, descent, and landing. JPL will use this platform as a baseline to plan variations for future mission.

2. MISSION DESIGN OF ATMOSPHERIC OCCULTATION CONSTELLATION

Traditional planetary atmospheric radio occultations using a single spacecraft with a link to Earth, are ultimately limited in the spatial and temporal coverage they can provide. The use of dedicated CubeSats would enable much higher spatial and temporal coverage, because of spacecraft-to-spacecraft links. Our team applied the very successful local technology innovation of spacecraft-to-spacecraft links (i.e., crosslink) at the Earth to other solar system bodies [3].

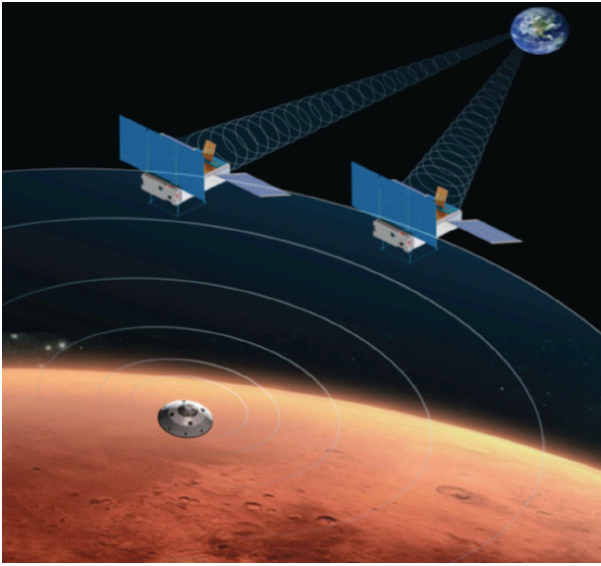


Figure 1: Illustration of Mars Cube One (MarCO) performing relay function from a Mars lander to Earth. In practice, MarCO will provide the relay function for the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission.

Our team investigated the link budgets, transmit and receive options, and signal band selection consistent with CubeSat resources. The latter include cost, size, power, mass, longevity, and radiation tolerance. Many elements of interest have been independently developed by other teams to meet various mission scenarios and a comprehensive examination drew on all of previous experiences to reach the next expected breakthrough via innovative mission configurations with the appropriate instrumentation [3].

Although our focus has been Mars science, the system can be customized to other planetary targets of interest. This research specifically pursued the following priorities:

1. Prototyping the crosslink science instrument with the capability for not only links between CubeSats but also for links between CubeSats and large satellites as well as links between multiple large satellites.
2. Developing a plan to raise the technology level with a path to flight systems with crosslink radio science capabilities, including a technology plan for the Iris radio, the current deep-space transponder standard.

In the process, we have accomplished the following:

- **Architecture study:** We completed an architecture study via JPL's A-Team with the participation of scientists from the Mars program office to mature a science traceability matrix. Key community science goals were identified with specific measurement requirements. Of particular note were specific requirements for atmospheric temperature accuracy as well as for measurement distribution over the planet to achieve a compelling science investigation, including longitude, latitude, season, and local time coverage (see Figure 2).
- **Requirements definition:** After defining scientific requirements, relevant engineering specifications were derived. Detailed calculations were performed for a maximum inter-spacecraft distance of 12,000 km to determine the required transmitter power to meet science objectives. Antenna gain of 9 dBi (receive and transmit modes) were assumed, based on the MarCO X-band medium gain antenna design. For open loop phase tracking, powers in the range 2 W–5 W are needed, compatible with current Iris capabilities.
- **Navigation study:** A detailed study was completed to determine if the smallsat orbits would be of sufficient accuracy to meet the science requirements. We assumed tracking contacts between the CubeSats before and after each occultation event as well as frequent contacts with the orbiter, the latter having well known position and velocity. Orbiter navigation is achieved independently using Deep Space Network (DSN) radio-metrics.
- **Systems engineering analysis:** We performed a high-level analysis to verify that the power budget would close the link. CubeSat components were based on MarCO with modifications identified for radio occultation science. For a 6U CubeSat implementation, the CubeSat mass is estimated to be 12 kg, and gimbaled solar panels can provide ample on-orbit power. We also explored a potential future Mars orbiter mission as a viable host and deployment vehicle and addressed the frequency for proximity communications, as well as the orbiter's function as a data relay satellite.
- **Orbital simulations:** Simulations to estimate the numbers and locations of retrieved atmospheric profiles expanded on prior work. Multi-year simulations allowed improved understanding of how measurement coverage varies on seasonal timescales. Differential precession rates for nearly sun-synchronous (inclination 92°) and lower inclination orbits (72°) were taken into account. Figure 2 illustrates the substantial increase in atmospheric occultation measurements that would be possible with a dedicated CubeSat mission.
- **Iris re-design:** We proposed a re-design of the Iris CubeSat transponder in order to support the new

science objectives. A transmit/receive module design was developed to convert Iris to a simultaneous dual one-way link configuration. Candidate transmit/receive X-band frequencies and design topologies were considered, and one design seemed most promising for achieving the needed sensitivity requirements and isolation of the receiver [4].

We have successfully advanced the design of a CubeSat-based occultation constellation at Mars that can accomplish needed scientific objectives as defined by the science community. A point design that relies on MarCO heritage, including the Iris communications radio as a key component, fulfills our objectives of exploiting communications technology for scientific investigations.

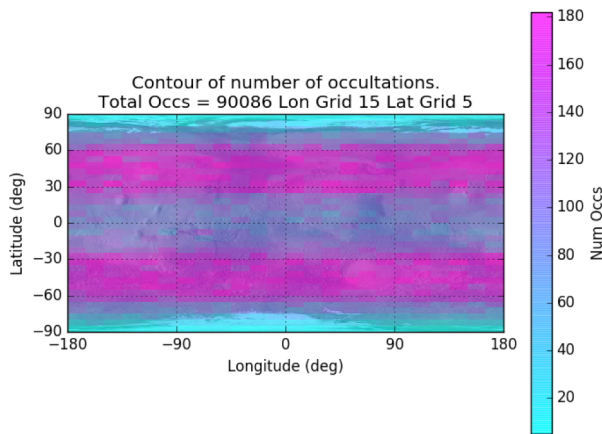


Figure 2: Number of profiles achieved with 4-satellite configuration after one Martian year (approximately two Earth years) over a 15°x5° longitude/latitude grid.

3. FIELD-TESTING AND MODELING OF SOIL PROPERTIES FOR SCATTERING EXPERIMENTS

Bistatic radar experiments have been carried out at the Moon and several planets and moons as far as Titan and Pluto. They reveal scientific information on the electrical properties and surface roughness as well sub-surface material. In an effort to engineer a new method of uplink bistatic radar, our team focused on the application of both bistatic and monostatic radar measurements using a potential Mars helicopter as the signal source. The simplest approach was to use the planned 900 MHz telecom link as a source for the bistatic radar signal; transmit by helicopter and receive at the rover. Analysis of simple RF signal propagation geometry and electromagnetic modeling of surface and sub-surface reflections shows that a telecom link with varying geometry can produce a power level profile that includes a bistatic radar signature indicative of the subsurface electrical properties and the subsurface layering. Our team carried out field tests of a simulated helicopter-to-rover 900 MHz bistatic radar signaling using the Arroyo Seco dry sand wash east of JPL (see Figure 3). This is the same historic location used for initial rocket engine tests by Caltech students that later founded JPL.

Figure 4 shows a cartoon schematic of the equipment and geometry used for the field tests, where the helicopter was simulated with an antenna on top of an extendable pole as the RF source and a simple model of the Mars 2020 “rover deck” as the RF receiver. For actual operations on Mars the minimum ground distance between helicopter and rover is 100 m. Field test use of a shorter 5 m to 10 m ground range enabled a wider range of signal geometry given the maximum height to which we could elevate our analog helicopter system (7 m). Antenna height was varied from 2.5 m to 7 m, equivalent to elevation angles of 20° to 40°. The rover was modeled with a 1:1 scale deck positioned 1 m above the ground, with the receiving antenna on the rover mounted 10 cm above the deck. The 10-m range used here increased received signal levels by 20 dB, relative to a 100 m Mars operational range, making for clearer signal measurements.

One test site was at the lowest level of a sand wash with underlying sand and rock debris, assumed to be of depth of 3 m or more. A reference signal measurement was obtained by placing a metal screen covering the first Fresnel zone of the ground reflected signal forcing near 100% reflection at the surface. Figure 5 shows the bistatic signal reflection result, blue curve vs the curve fit model that predicts the detection of two layers with the second layer interface at 0.21 m below the surface. Digging into the sand, we found damp sand started about 45 cm down from surface. Not an exact fit to our model estimate but the sand was very damp by ~45 cm down with moisture perhaps rising higher in other locations. This approach does not use radiograms nor any other method to attempt to “image” the structures that are causing the reflections. It assumes that some of the properties of the materials are known, e.g., dry silicate sand material underlain by a denser wet layer of sand. We used measured data as input to a gradient search algorithm that searches constrained model space to produce one or more best fit solutions to the layer dielectrics and layer depths.

4. IRIS RADIO FOR CUBESAT SCIENCE

Radio science investigations utilize spacecraft transponders as their primary instrument and have performance requirements that define the success of the experiments, and nearly all solar system spacecraft include radio science as part of their scientific instrument complement. With the advent of inexpensive small spacecraft and transponders, “daughter-ships” with radio science as the only instrument may become possible, allowing targeted investigations of atmospheres, gravity fields, and other phenomena.

This research aims to advance the design of CubeSat telecommunications technologies to perform cutting edge solar system radio science using the latest Iris radio as a baseline. Iris is a JPL-designed software-defined radio (SDR) for small spacecraft. Initial versions are baselined for MarCO and multiple CubeSats planned as secondary payloads on NASA’s EM-1 mission.

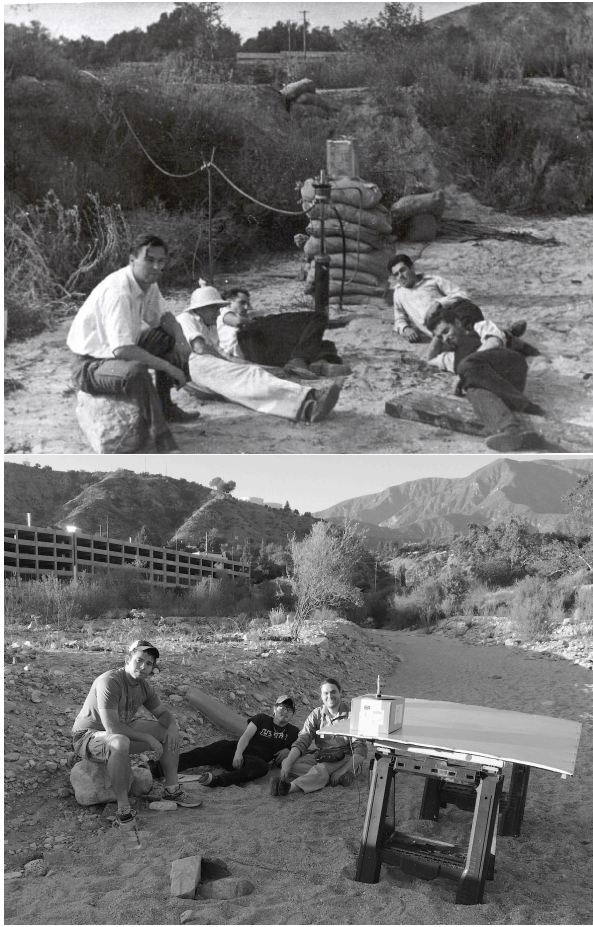


Figure 3: Upper panel is a 1936 photo of rocket motor tests at the site that later became JPL (Rudolph Schott, Apollo Milton Olin Smith, Frank Malina, Ed Forman and Jack Parsons; Lower panel is a 2016 photo of bistatic radar testing at the same site (Joshua Miller, Curtis Jin and Emmanuel Decrossas).

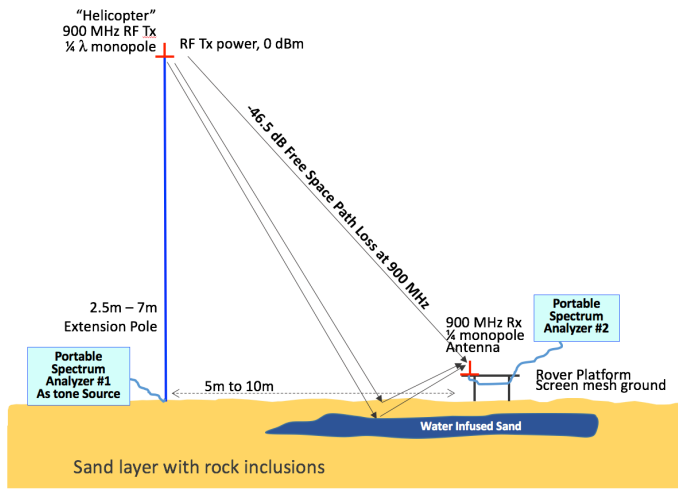


Figure 4: Schematic of experimental testing.

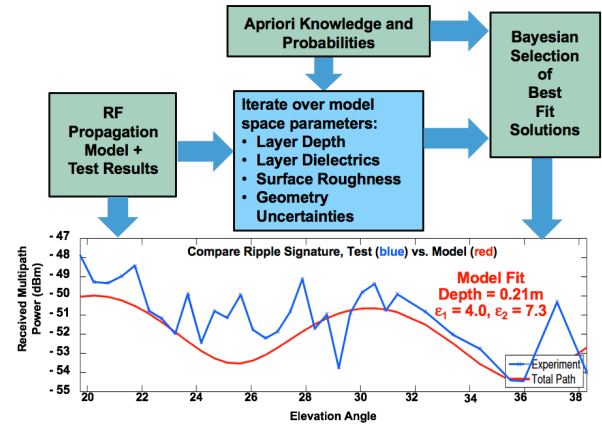


Figure 5: Example 900 MHz test results using variable signal geometry and gradient search algorithm to determine best fit for dielectric constants and layer thickness.

We will examine the current Iris radio-metric performance and identify specific achievable upgrades such as improved 1-way and 2-way Doppler and ranging precision, broader band open loop record, new open-loop recording functions, simultaneous dual frequency support, and bistatic transmit and receive signaling modes. We will evaluate potential enhancements to Iris provided by integrating data processing, data storage, data formatting, and data transfer to onboard data handling systems. We will also document the required engineering upgrades, modes, and features that enable Iris to successfully address each of the identified high priority science uses.

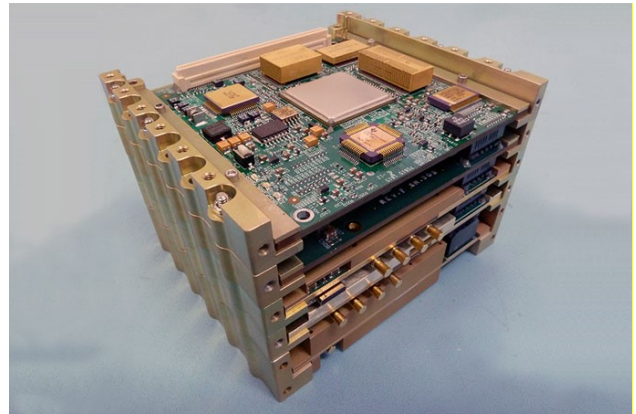


Figure 6: Iris software-defined radio for small spacecraft.

5. MINIATURE ULTRA-STABLE OSCILLATORS

Ultra-Stable Oscillators (USO) have been at the heart of the instrumentation for planetary atmospheric occultations since the Voyager mission. Their highly successful uses to date have led to significant discoveries in planetary atmospheric dynamics as well as Saturn's ring structure. However, in the era of small spacecraft, USOs are bulky and can be difficult to accommodate causing a significant limitation in planning future Radio Science atmospheric occultations with small spacecraft. Such spacecraft offer low-cost opportunities to

more completely characterize solar system atmospheres, ionospheres, and rings with greatly increased geographic and temporal coverage than available with only links from large spacecraft to Earth. Moreover, the next generation micro-photonic USO could enable GRACE type crosslink gravity measurement capabilities using small spacecraft.

The primary goal of this research effort is to investigate new approaches that will lead to a USO that can fit into the size and power confinement of small spacecraft while maintaining traditional USO performance at the level of $1\text{e-}13$ for 1 to 100 second integration times. We will investigate the feasibility of reducing the size of traditional oven-based quartz oscillators as well as novel RF micro-optical oscillators possibly capable of providing $1\text{e-}14$ stability.

Science measurements using telecommunication links are done by recording the phase shifts of the USO-referenced signal. Ultra-stable oscillators with better phase stability enable significantly improved measurement sensitivities. This stability is determined by the link signal source, typically a stable oscillator. The best space-borne USOs from multiple suppliers are based on a highly temperature-stabilized quartz oscillator. Current USO volume exceed 1U ($10\times10\times10$ cm), not a good fit for CubeSat applications.

Quartz-based USOs require very precise thermal stability achieved via an enclosed oven system, signal processing (e.g. 1st and 3rd harmonics for temperature sensing) and accompanying electronics. The thermal control mechanism is a prime candidate for re-design and miniaturization. The requirement of thermal isolation and control for a USO is determined by the dependence of frequency on temperature. The quartz plate can be cut along a certain direction to achieve the lowest temperature coefficients of its vibration modes. Since the temperature coefficients are still not zero, the control and stability of the crystal's thermal environment must be improved, which typically requires large system size and power. We will investigate methods of reducing size and improving performance of the thermal stabilization system, including use of advanced numerical thermal modeling and utilization of recent advances in material technologies.

Another well-established approach relies on synthetic composite ultra-low expansion (ULE) glass that can achieve nearly zero thermal expansion coefficient, allowing optical oscillators to achieve $1\text{e-}16$ stability, an improvement of 3 orders of magnitude compared to the best quartz USO. Such optical oscillators are typically 3U or larger in volume. Recently, we explored the feasibility of a composite optical micro-disk resonator containing ULE material. Such a compound resonator combines the stability of optical oscillators with the compactness of quartz crystals and holds the potential to be miniaturized for smallsats. An optical micro-resonator oscillator with microwave outputs is a new type of a USO that we propose to investigate.

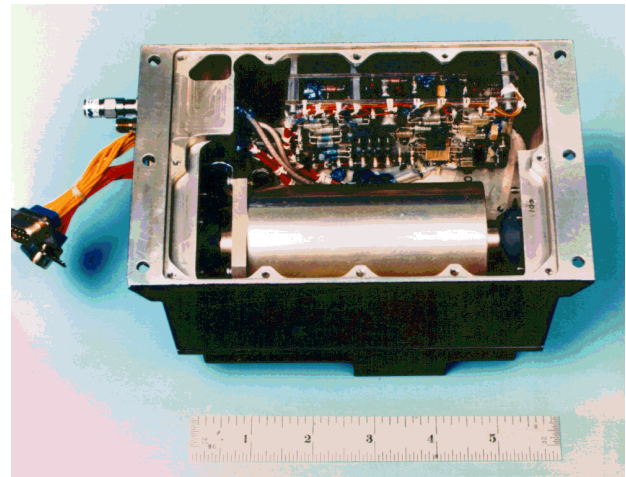


Figure 7: An image of a USO on a planetary mission (Mars Global Surveyor) considered too large for CubeSats.

6. ADVANCED RADIO-METRIC CALIBRATIONS AT THE DEEP SPACE NETWORK

The aim of this research is to provide the next order of magnitude improvement in interplanetary spacecraft Doppler tracking precision from the DSN, which currently defines the state-of-the art. These improvements would have the most scientific impact in the determinations of the gravity fields of solar system bodies, both for improving results from bodies already visited and providing the first information for others. Interior structures of bodies, reconstructed from gravity field measurements, provide insight into their formation history and subsequent evolution. In the case of icy moons, the determination of the existence and details of sub-surface oceans is crucial to establishing whether they may present possible habitats for life. For any potential human exploration of small bodies (including Phobos and Deimos), a recognized strategic knowledge gap is the porosity of these bodies including the possible existence of interior voids. One of the few remote sensing means for studying planetary interiors is via the technique of spacecraft precision Doppler tracking by the DSN. This technique is currently being used on the Juno mission, determining the interior structure of Jupiter, and was recently employed during the Cassini Grand Finale measurements of Saturn's gravity field. Over the past decade, the interior structures of a number of other solar system bodies have been revealed, including Titan, Enceladus, the Moon, Mars, Vesta, and Ceres.

Doppler tracking accuracy has seen a number of advances over the past two decades (e.g., coherent Ka-band links to the Cassini and Juno spacecraft, and multi-frequency calibrations of charged media). Reviews of the state of the art in the field concluded that the next largest error source in the noise error budget is antenna mechanical noise due to mechanical vibrations within the relatively large DSN antennas. The effect is described in detail in [5] along with a proof-of-concept demonstration for a technique that can

reduce the effect of antenna mechanical noise. Solely reducing antenna mechanical noise will not be sufficient, however. Cassini and Juno investigations have demonstrated that wet tropospheric fluctuations are also a dominant error in Doppler, if not calibrated to a high level, and current water vapor radiometers used to correct for the wet tropospheric fluctuations are beyond the end of their design life. Ensuring the next generation of water vapor radiometers are utilized and the technique of robust antenna mechanical noise cancellation is understood and implemented will enable the next level of precision in the study of the interior structures of Solar System bodies.

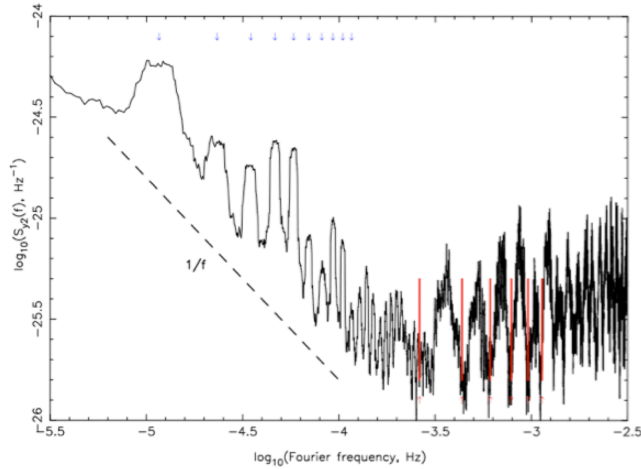


Figure 8. Spectrum of 2-way fractional Doppler fluctuations, corrected for plasma and tropospheric fluctuations, taken during the 2001-2002 Cassini gravitational wave experiment smoothed to frequency resolution of $\approx 7 \mu\text{Hz}$. Six frequencies of the nulls of the antenna mechanical noise transfer function, $k/(\pi T_2)$ where k is an odd integer and T_2 is the average two way light time over the observations (5730 sec), are marked with the red lines towards the right of the figure.

The Task of developing advanced radio-metric calibration techniques has two objectives, both aimed at advancing the next breakthroughs in radio science:

1. Review the expected improvement in Doppler data from the implementation of time-delay antenna mechanical noise when incorporating a smaller, stiffer antenna as an additional radio link. Survey existing antennas, such as the millimeter-wave antennas at Caltech's Owens Valley Radio Observatory, to assess whether a near term demonstration is feasible. A demonstration can then be carried out.

2. Design the next generation DSN advanced Water Vapor Radiometer using JPL technologies, commercial vendors, and Caltech's Radio Astronomy. Consider the design and performance of the next generation radiometer procured by the European Space Agency, and also consider integrating the radiometer with the spacecraft tracking antenna.

7. SUMMARY

This paper presented a path for advancing the utilization of small spacecraft for planetary atmospheric, surface, and interior structure using radio links. Accomplishments to date along with plans for the near future were summarized.

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BIOGRAPHY



Sami Asmar is the manager of strategic planning and formulations at the Interplanetary Network Directorate at NASA's Jet Propulsion Laboratory, California Institute of Technology, Project Scientist for the GRAIL lunar mission, and a co-investigator for Radio Science on US and European deep space missions. He is the recipient of 3 NASA Exceptional Achievement Medals, among other awards. He has been leading JPL research initiatives in the science and technology of radio and laser link utilization for planetary exploration.



Joseph Lazio is Chief Scientist of the Interplanetary Network Directorate at the Jet Propulsion Laboratory, California Institute of Technology that manages the Deep Space Network. He received his Ph.D. from Cornell University, was a U.S. National Research Council Research Associate at the U.S. Naval Research Laboratory and a Radio Astronomer at NRL before joining JPL. He is the Project Scientist for the Sun Radio Interferometer Space Experiment mission concept and was the Deputy Principal Investigator for the proposed Dark Ages Radio Explorer (DARE). He has served as Project Scientist for the Square Kilometre Array; Deputy Director of the Lunar University Network for Astrophysics Research; and Project Scientist for the U.S. Virtual Astronomical Observatory. He also observes routinely with the world's premier ground-based radio telescopes including the Expanded Very Large Array, the Very Long Baseline Array, the Green Bank Telescope, the Giant Metrewave Radio Telescope.



David H. Atkinson received a B.A. in Astronomy/Physics from Whitman College, M.S. in Applied Physics from Stanford University, and a B.S. and Ph.D. in Electrical Engineering from Washington State University. From 1981-1986 he worked as a system engineer on the NASA Galileo probe mission at NASA Ames Research Center, and from 1989 until 2016 he taught in the Electrical and Computer Engineering Department at the University of Idaho in Moscow, Idaho. He led the Galileo probe Doppler Wind Experiment, and was a Co-Investigator of the Cassini Huygens Titan probe Doppler Wind Experiment, and Chair of the Huygens probe Descent Trajectory Working Group. He is currently a senior system engineer at the Jet Propulsion Laboratory.



David J. Bell is the manager of the Flight Telecommunications Section 337 at the Jet Propulsion Laboratory and has over 35 years of experience in all aspects of flight and ground radio system design including modulation, coding, antennas, propagation and interference mitigation. He has published numerous telecom technical papers and holds several patents related to antennas and coding systems for telecom operations in difficult propagation and signal environments. In addition, he was the system engineer for all aspects of the initial development, flight build and test of the Electra Software defined radio subsystem that is now flying on the MRO, MSL, MAVEN and TGO spacecraft. He has also taught satellite and network applications at the UCLA engineering extension program.



James Border received a Ph.D. in Mathematics from U.C. San Diego in 1979. He has been at JPL for more than 36 years. An expert in analysis of radiometric data and applications of VLBI to spacecraft navigation. He leads the development of the DSN ground data system to enable high accuracy spacecraft angular position measurements. His work has included system engineering, receiver design, signal processing algorithm development, error analysis, and calibration techniques to improve accuracy.



Harvey Elliott received a B.S. in Aerospace Engineering in 2009 and an M.Eng. in Space Systems in 2010 from the University of Michigan, Ann Arbor. He is a Ph.D. candidate at the same university in Climate and Space Sciences. Harvey has conducted two field campaigns with Dr. Nilton Renno at Mars analog sites in Southwestern U.S. and African Sahel, including checkout of Rover Environmental Monitoring System, an instrument on the Mars Science Laboratory Rover. His research interests include interferometric measurements of subsurface soil properties, microwave measurement of soil water content, and the potential for liquid brines on Mars.



Ivan S. Grudin, Caltech PhD in Physics, 2008, develops photonic and microwave technologies for space applications at JPL. He has more than 15 years of research experience in optical resonators, numerical modeling, spectroscopy, material science, precision measurements, ultrafast nonlinear and quantum optics, RF and THz photonics, frequency combs and cavity optomechanics.



Anthony J. Mannucci is Supervisor of the Ionospheric and Atmospheric Remote Sensing Group at NASA's Jet Propulsion Laboratory, a Principal Member of the Technical Staff, and a Senior Research Scientist. His group focuses on scientific applications of Global Navigation Satellite System

signals, such as the US GPS. Dr. Mannucci leads a group that produces atmospheric science data from NASA-developed GPS radio occultation receivers onboard the CHAMP, SAC-C, GRACE and COSMIC missions. He has served as a member of the NASA CLARREO mission science team. He manages development of the Global Assimilative Ionosphere Model jointly developed at the University of Southern California and JPL. He is lead author on a review article published in 1999 concerning the use of GPS receivers for ionospheric measurements, and holds patents pertaining to the design of differential GPS systems and using GPS data for remote sensing purposes.



Robert A. Preston received a PhD in Aeronautics and Astronautics from M.I.T. in 1972. He has been with JPL 44 years and is currently a principal scientist. Previously at JPL he was chief scientist of the Interplanetary Network Directorate, astrophysics program manager, space VLBI project scientist, and supervisor of an

astronomical research group. He has been an investigator on several planetary mission radio science experiments and U.S. scientific team leader for balloons that flew in the atmosphere of Venus.

